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Summary Hazards Report for Critical Experiments With The HOTCE Reactor

J. A. Hoefer

GENERAL ELECTRIC
ATOMIC PRODUCTS DIVISION
AIRCRAFT NUCLEAR PROPULSION DEPARTMENT

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ABSTRACT

A solid-moderated critical assembly designed to operate at elevated temperature is described. The experiment program and operating procedures planned for various temperatures are outlined. The hazards of operating the HOTCE in the Low Power Test Facility at the Idaho Test Station have been analyzed and the results set forth in terms of energy and fission fragment release as well as the effect on the surrounding area.

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1. INTRODUCTION - SUMMARY

The Hot Critical Experiment (HOTCE) is an elevated-temperature critical experiment designed to obtain information on temperature coefficients of solid-moderated reactors, to develop a theory consistent with this information, and to develop measurement techniques with a high-temperature reactor. It is to be operated in the Critical Experiment (CE) cell of the Low Power Test Facility (LPTF) at the National Reactor Testing Station in Idaho.

The design of the reactor and the LPTF allows considerable flexibility in performing the various experiments for which the reactor was designed. The important mechanical characteristics of the HOTCE are as follows:

1. Structure: a right hexagonal prism with an effective core 30 inches long and 51.6 inches in diameter.
2. Core: a hexagonal prism with modified corners. It will normally contain 151 cells in a hexagonal matrix and will have provisions to add three cells in each corner for a total of 169 cells. The cells consist of hydrided zirconium 35.5 inches long, around 30-inch-long fuel elements. Each fuel element consists of fuel-bearing stainless-steel wire 1/8 inch in diameter wound in a helix around a threaded ceramic tube. The initial loading of 151 fuel elements contains 45.0 kilograms of U^{235}. A maximum loading of 50.4 kilograms of U^{235} can be achieved with insertion of 169 fuel elements.
3. Radial reflector: beryllium 4 inches thick by 30 inches long. Additional 2-inch reflector pieces are provided, and thus a reflector-thickness range of 2 to 6 inches is possible.
4. End reflector: ends are unreflected except for the partial reflection given by the 2.75-inch moderator overhang at both ends of the core, the ceramic end pieces, and the stainless steel tube sheets. Small pieces of beryllium are provided to fill in the spaces resulting from not having a truly hexagonal array.
5. Heatup: the temperature of the HOTCE core is elevated electrically by resistance heating of the combination fuel-heating elements and space heaters attached to the radial reflector.
6. Control and safety: B_4C absorber rods, which can be connected to an actuator or inserted manually, are used for control and shutdown. The control rods are coupled by an electromagnet to a motor-driven lead screw, which is a combination control-scram type actuator. Rods moved out of the core compress a coil spring that will fire the rods back into the core from any position if the current is shut off. At least 2 percent in reactivity is available for safety before the assembly can be made critical.
7. Methods of shutdown: electronic, depending on neutron or gamma flux levels; manual; and power failure. Initiating events result in the safety rods being inserted in less than 150 milliseconds and the table halves being separated at the rate of 6 inches per minute.
8. Interlocks: control rods can be withdrawn only if (1) the source is in the reactor or the flux level is greater than a present minimum and (2) the period is greater than

a present minimum. At least 2 percent in reactivity will be withdrawn for criticality at design temperature. The safety rods may be withdrawn only when the table halves are fully separated. No provision is made for bypassing interlocks.

The prime purpose of the HOTCE is to study the effects of varying the temperature of solid-moderated reactors. The following are typical of the type of experiments to be performed.

1. Determine the temperature coefficient as a function of temperature.
2. Map the gross radial and longitudinal power at various temperatures.
3. Study the effects of heating only specific parts of the core, such as the fuel wire and reflector.
4. Study the effect of various temperature profiles radially across the core.
5. Compare the value of several possible control rod materials as a function of temperature.

In addition, by removing any fuel element with its supporting ceramic tube, a test hole is available for such things as testing low-level, high-temperature sensors and fine power mapping of a modified, design-type fuel element.

2. DESCRIPTION OF SITE, FACILITIES, AND REACTOR

2.1 SITE

The Low Power Test Facility (LPTF) is located in the northeastern part of the National Reactor Testing Station (NRTS), approximately 1-1/4 miles southeast of the Assembly and Maintenance (A and M) portion of the ANPD area. The NRTS is situated on the Snake River plain in southeastern Idaho, a location that is remote from heavily inhabited sections. There is no agriculture within the NRTS and very little surrounds its immediate boundaries. The surface of the area is nearly flat, and the elevation is 4792 feet at the LPTF. Surface drainage is good. Several streams flow into the NRTS and disappear into the ground. Natural drainage at the LPTF is to the south, southeast.

2.2 ASSOCIATED FACILITIES

The layout of the LPTF is given in Figure 1. The test cells are of poured-concrete construction, and the control and equipment building is of pumice-block construction. The test cells have a common wall between them; it is 4 feet thick and extends 4 feet below floor level. The continuous wall that separates the test cells from the control and equipment building is 5 feet thick for a height of 30 feet; then it steps from the outside in to a thickness of 18 inches. The outside wall of the Initial Criticality (IC) cell is 2 feet thick, and the outside wall of the Critical Experiment (CE) cell is 3 feet thick for a height of 30 feet and for a distance of 18 feet from the 5-foot wall. The rest of the wall is 2 feet thick. The ceilings of both cells are of reinforced concrete 1 foot thick with built-up roofing on top. The ceiling height is 43.5 feet to accommodate an overhead crane in each cell. The entrance for equipment to the cells is through a doorway 22 feet wide by 30 feet high. The doors are roll-up sheet-metal doors of standard roll-up-door thickness. The personnel entrance to the cells is via doors in the side walls. The door in the IC cell is located 39 feet from the 5-foot wall and may be reached through a pumice-block passageway built on the outside of the cell. The door in the CE cell is 18.5 feet from the 5-foot wall and is reached by going through a room that houses an air-conditioning unit for the cell. Precautions were taken when constructing all cell walls to prevent any pipes or conduits from going straight through the wall. All pipes or conduits are dog-legged twice to prevent straight-through shine of radiation.

The control rooms are directly behind the cells on the opposite side of the 5-foot wall. The data room is between the control rooms. The control rooms house a semicircular control console, which holds all the circuits necessary for operation of the reactors. Information recorders and instruments are mounted on panels that flank the console. The operation crew can monitor the cell room during operation by means of closed-circuit television with the receiver mounted on one of the flanking panels.

The electrical conductors from the control console and from the panels drop into cable trenches in the floor, from there into a tunnel via wire ways, and into a terminal box in the tunnel. From the terminal box they run through conduits under the 5-foot wall, up into a box on a pad in the cell, and terminate to quick-disconnect connectors mounted on

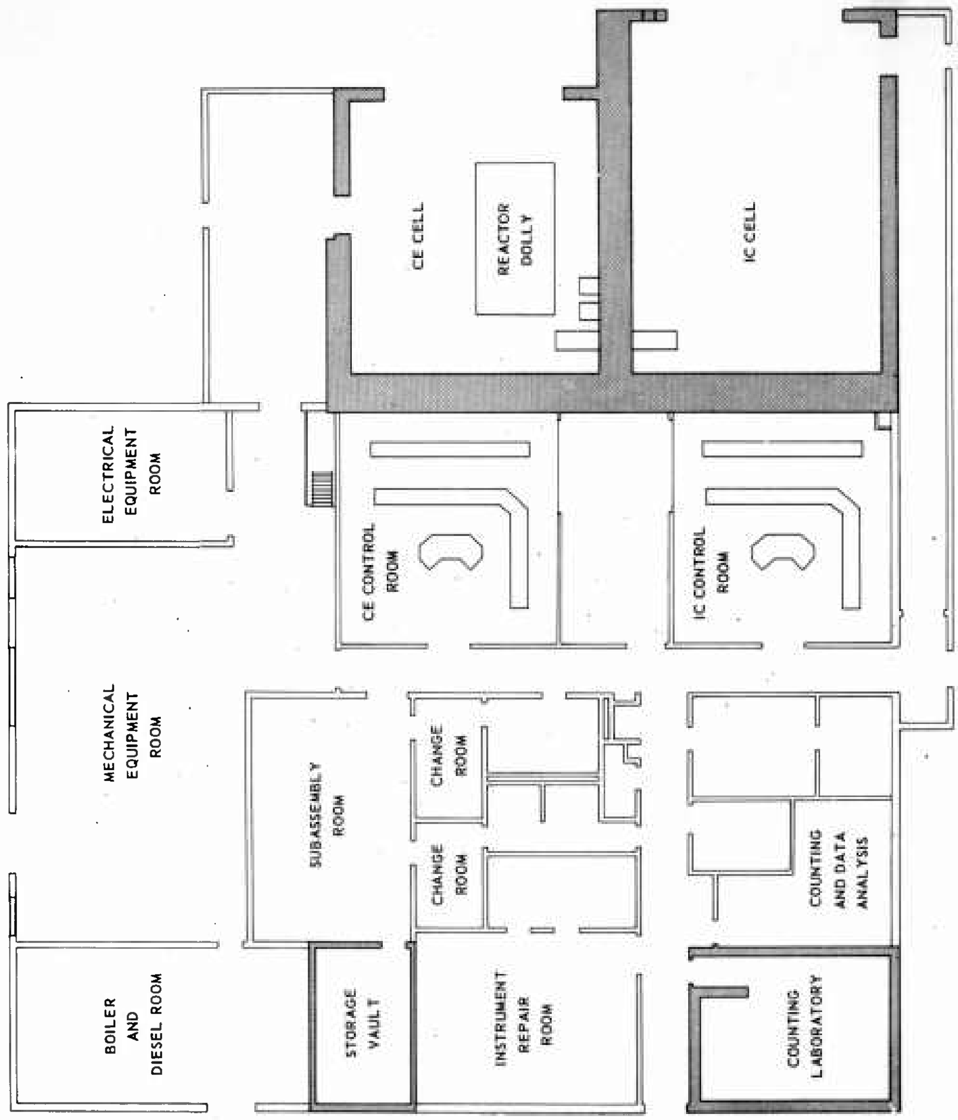

Fig. 1 – Low Power Test Facility, plan view

the face of the box. The nuclear channels are run directly in conduits from the cell room to the cable trench directly below the associated equipment. A surplus of conduits has been installed for future use of nuclear channels or control circuits.

Included in the control and equipment building is a counting room, which is constructed of 16-inch poured-concrete walls and a concrete ceiling to hold the background level to 0.1 mr per hour. Also included is a storage vault with a four-number combination vault door, and with poured-concrete walls and ceiling that has an entrance-proof ventilation system.

Office space is provided in the control and equipment building for use by operating people associated with the facility. An office is also provided for use by health physics people. There are sufficient rest-room and change-room facilities near the assembly room.

The assembly room is used for loading foils on fuel elements and for assembly of fuel elements. It has a battleship linoleum floor for easy decontamination and a stainless steel sink for decontamination of small components. The floor drain and the sink drain, as well as the wash bowls in the change rooms, drain into an underground contaminated-liquid tank on the outside of the building. The liquid from this tank can be pumped out into a tank truck and removed to the A and M area for disposal. A special pump is installed in the tank for this purpose.

Also included in the control and equipment building is a room that provides for instrument and control repair, office space, and storage space for instruments and spare parts.

For security purposes, the facility is surrounded by a security fence with one personnel entrance and one vehicle entrance, both of which are guarded by security personnel. A signal system is incorporated in the facility to notify the main guard station at the A and M area in case of fire, tampering with the vault, and opening of unauthorized doors.

For radiation protection, fences are installed adjacent to the rear of the test cells and extend to the security fence to prevent access to the area outside the test cells during operation. The fences have gates with locks. Surrounding the security fence is a radiation fence that prohibits an approach of less than 1000 feet in the radiation path. At its maximum separation distance it is 1500 feet from the front of the test cell doors.

The electrical system consists of a 13.8-kv primary circuit and a 480-volt secondary circuit obtained through outdoor transformers. Four transformers are furnished: one for the well house, one for instrument power, one for heating panels in the cells, and one for general lighting and power. Appropriate 440-volt switchgear is used for control and protection of the electrical circuits. In addition to the regular electrical feeds, there is a diesel generator that is used in case of power failure to supply power for table separation, boiler operation, guardhouse lights and heat, perimeter lighting for security, water system, emergency lighting, and ventilation system.

The water system consists of a well that is located approximately 500 feet to the east of the main facility. The well house contains a chlorination system and a 400-gpm electric-driven pump with a 40-horsepower gasoline engine coupled through a disconnecting clutch for emergency use. There is a 75,000-gallon storage tank located by the main facility, and constant water pressure is obtained by the use of two centrifugal pumps that run continuously.

The ventilation system consists of refrigerated air in conjunction with steam heat for the control rooms, data room, and counting room, and evaporation cooling in conjunction with steam heat for the rest of the equipment and control building. The IC cell has a steam heating system and a ceiling exhaust fan, and the CE cell has a refrigerated air-conditioning system and a steam heat system. The CE cell also has an exhaust duct in the ceiling for air flushing when necessary. The duct is designed to relieve at 1/8-inch water-gage pressure. Steam heat and hot water are supplied for two low-pressure, automatic boilers.

The sanitary sewage system is made up of normal drains and feeds through a chlorination plant into a settling tank; the chlorinated liquid is put into the underground water system via a well.

The fire protection system consists of hand CO_2 extinguishers and a fire hydrant system, which is fed from the water system and can be used by the fire protection pumper truck from the A and M area of ANPD. In addition, the test cells have a CO_2 system for flooding the cells with CO_2 in case of large fires that could not be easily extinguished.

Cooled, dried air is supplied at 280 cubic feet per minute at 125 psi by two electric-driven compressors.

Heating panels have been installed in the test cells for distribution of power to the heating elements of the reactor when desired. Electrically operated 440-volt circuit breakers are provided for this purpose.

2.3 HOTCE DESCRIPTION

2.31 REACTOR DESCRIPTION

The Hot Critical Experiment (HOTCE) reactor has a hydrided zirconium moderator and a beryllium reflector. The core normally contains 151 cells and has the shape of a hexagonal prism with corners modified as shown in Figure 2. Provisions are made, however, to add three cells in each corner if desired. This would fill out the hexagonal shape of the core with a total of 169 cells.

The temperature of the HOTCE core is elevated electrically by resistance heating of the combination fuel-heating elements. If the reflector is to be heated, the strip heaters placed against the outer surface of the beryllium are used.

A perspective view of the HOTCE core assembly is given in Figure 3.

Reactor Core Components

Fuel Elements - The fuel elements consist of fuel-bearing stainless-steel wire that is 1/8 inch in diameter and is wound in a helix around a threaded ceramic tube as shown in Figure 4. A cross section through the wire would show the core to consist of 93.2 percent enriched UO_2 mixed with stainless steel and a cladding of 310 stainless steel about 0.014 inch thick. The helical element formed by this wire has an outside diameter of 2.5 inches and a fueled length of 30 inches.

The initial loading of 151 fuel elements contains a uranium inventory of 45.0 kg. A maximum loading of 50.4 kg can be achieved with the insertion of all 169 fuel elements.

Moderator - The moderator consists of a zirconium bar, 35.5 inches long, hydrided to contain 4.1×10^{22} atoms of hydrogen per cubic centimeter. It has a modified hexagonal cross section with outside corners rounded. Some corners are modified to allow space for the insertion of control rods. The hydrided pieces are nominally 4 inches across flats and have a 3-inch-diameter hole longitudinally through the center.

Cell Assembly - A cell consists of the moderator bar with the fueled wire on its ceramic tube inserted and centrally located as shown in Figure 4. Ceramic pieces fastened

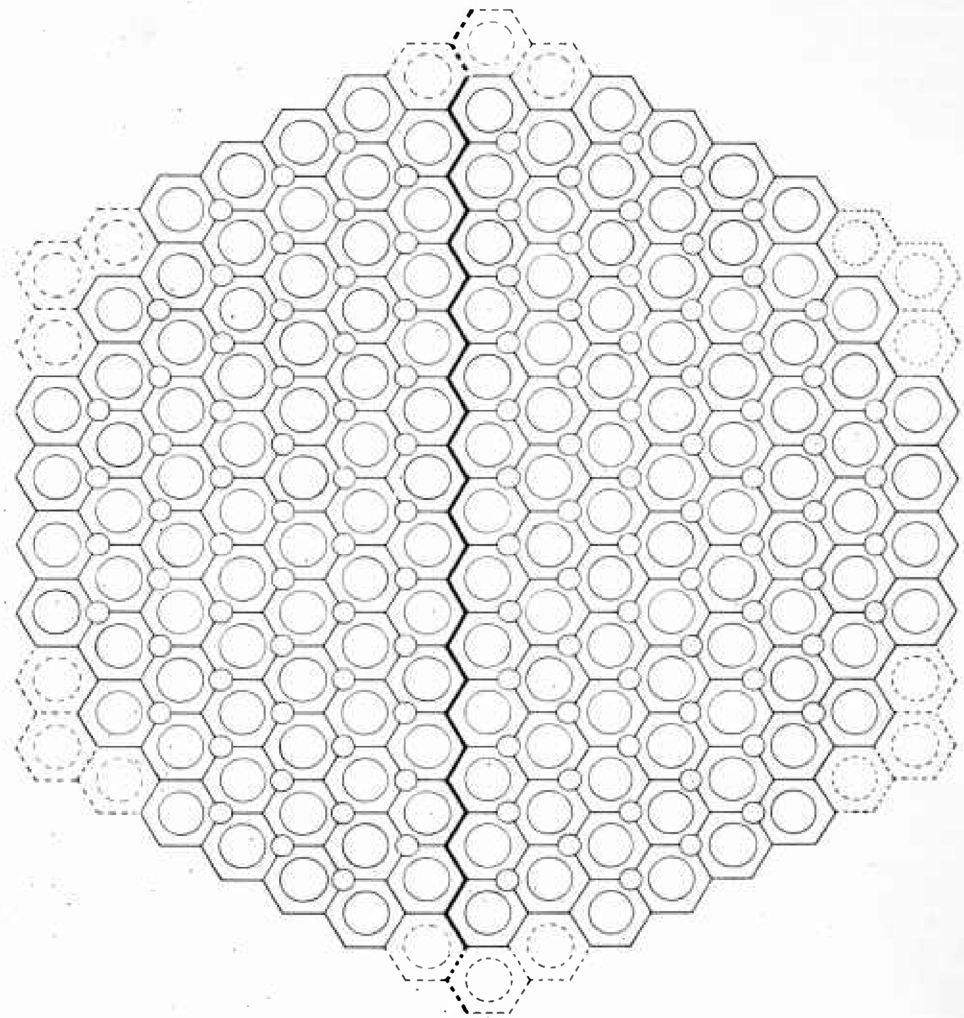

Fig. 2 – HOTCE core

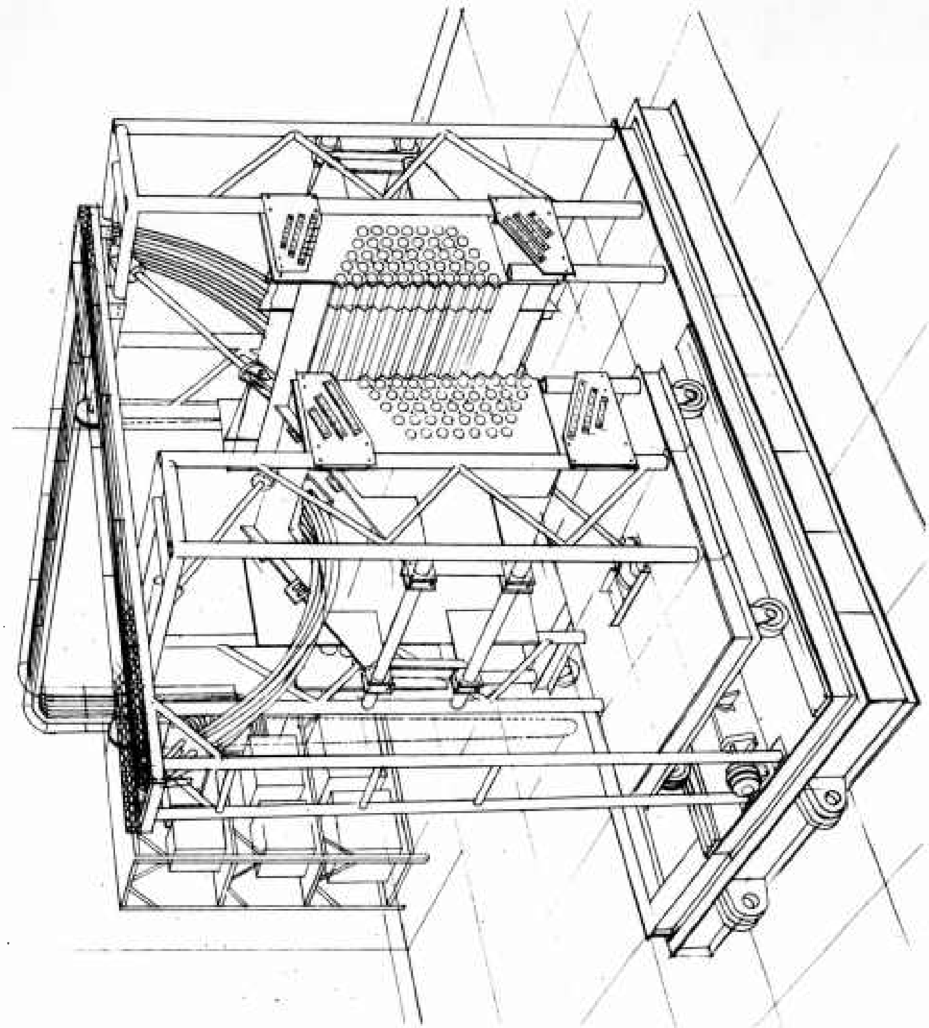

Fig. 3 – Perspective view of HOTCE

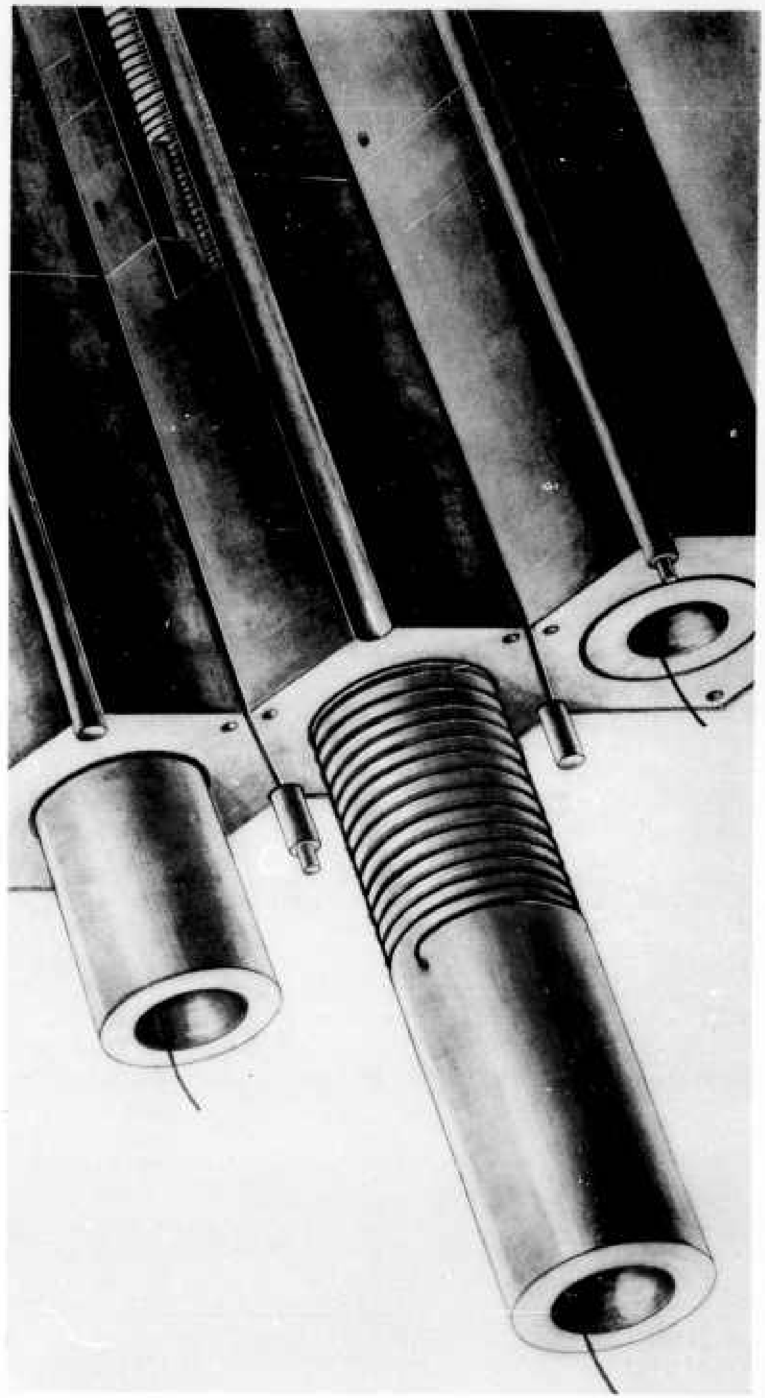

Fig. 4 – Fuel element and cell configuration, HOTCE

at each end of the moderator bar extend 6 inches from the ends of the moderator. These serve as insulation between the hot core and the tube sheets that support the core at either end.

Reflector - A beryllium reflector, nominally 4 inches thick by 30 inches long, surrounds the core on the six sides of the hexagonal prism. The ends are unreflected except for the partial reflection given by the 2.75-inch overhang of the moderator at either end of the 30-inch core, the ceramic end pieces, and the stainless steel tube sheets. Small pieces of beryllium are provided to fill in the spaces in the six corners that result from not having a true hexagonal array. These pieces may be removed and replaced with fuel cells. Additional 2-inch reflector pieces can be substituted for the 4-inch sections or added to them to give a 6-inch reflector.

Reactor Structure - The reactor structure assembly is basically a split-table type. The hexagonal-prism-shaped core and reflector are mounted so that the fuel cells are horizontal. The core and reflector are then split vertically across corners of the hexagon. One half is mounted on a fixed table, the other on a movable table so that the two halves may be separated to give easy access to the center of the core and to provide a major negative-reactivity effect while personnel are working nearby. The four pieces of reflector that cover the top and bottom faces of the separated core halves are mounted on hinges at one end and may be moved away from the core to permit more rapid cooling of the central portion of the reactor.

Heating System - The fuel element wire acts also as a core heating element. The unfueled, stainless steel ends of the wire are extended through the tube sheets at either end of the core. At the back, or actuator face, of the core all of the wire ends are grounded to the tube sheet. At the other end of the reactor, a connector is provided for an electrical connection. The fueled wires can then be raised in temperature by resistance heating. The moderator bars become heated in turn by convection and radiation from the wire.

Strip heaters placed in grooves on the outside faces of the reflector pieces serve to heat the reflector.

The moderator and reflector are expected to attain a maximum temperature of 1300°F. During the heatup cycle the fuel wire will reach a maximum temperature of 1600°F. At this temperature the fuel-wire cladding has adequate corrosion and strength properties to minimize a possible failure.

Four heating control systems give separate control over four separate regions. In general, one region will be the reflector, and the other three regions will share the core area. Thus by proper connections and settings of the controls, it will be possible to mock up various temperature configurations that might be encountered in power reactors.

A blanket-type insulation, approximately 4 inches thick, will be fastened to the outside of the reflector to prevent excessive loss of heat.

2.32 CONTROL SYSTEM

Control rod positions are provided at the corner intersection of three adjacent moderator bars. There are a total of 122 possible positions for control rods, as shown in Figure 2. A control rod may be connected to an actuator, or it may be inserted manually. In either event, the control rods are identical. The active portion consists of boron carbide, 30 inches long. This is contained by a stainless steel tube with a 0.750-inch outside diameter and a 0.049-inch wall thickness. When fully inserted, the active portion is centered longitudinally in the core.

The actuators are a combination control-scram type. Either one, two, or three control rods may be connected to a single actuator. There are 26 specific locations for actuators. Any or all of these positions may have an actuator in place, depending on the circumstances of the experiment in progress. If all 26 actuators were installed, it would be possible to have as many as 78 controllable rods in the assembly. For any experiment it will be an operational requirement that enough actuators be installed so that rod value of at least 2 percent in $\Delta k/k$ will be withdrawn before the assembly is made critical. An interlock circuit assures that this minimum reactivity is provided. These rods, plus any additional rods in the fully or partially withdrawn position, constitute the safety rods for the experiment in progress.

The actuators are coupled by an electromagnet, which is positioned by means of a motor-driven lead screw. The control rod becomes connected magnetically when the actuator is driven to its fully inserted position. As the rod, coupled to the electromagnet, is moved out of the core, it compresses a coil spring that will fire the rod back into the core from any position if the electromagnet current is cut off. This will occur with a scram or shutdown signal or upon power failure. The actuators have a stroke of 30 inches and travel at a rate of 18.5 inches per minute. Switches are provided to give light indications on the console to indicate "rod in" or "actuator out" conditions for each actuator. In addition, a potentiometer is connected through gears to the lead screw to permit voltage readings that indicate intermediate positions of the actuator.

The movable table is driven by a lead screw actuated by a variable-speed motor. Switches placed along the path of travel change the speed as the table moves toward closure. Switches and speed settings are so arranged that the table moves 6 inches per minute until 6 inches from closure, then 3 inches per minute until the two halves are together. Reactivity as a function of table separation is given in Figure 5, and the time rate of change of reactivity as a function of reactor separation is given in Figure 6.

In moving apart, the two halves separate at the maximum velocity regardless of the starting position. This occurs with a scram or shutdown signal. Reactivity of the HOTCE assembly as a function of time after scram, shown in Figure 5, indicates that table separation can be used as a secondary means of shutdown, although it is considerably slower than the safety rods.

Source

A 10-curie Po-Be source is used for startup of the HOTCE. It is contained in a nickel-coated, wrought-iron container encased in an outer container of stainless steel.

The source may be inserted in any of the 122 positions provided for control rods and may be moved into or out of the core by means of a flexible shaft driven by a motor outside the core. When the source is removed from the core, it is inserted into an acrylic plastic container for the protection of personnel.

2.33 INSTRUMENTATION

Instrumentation may be divided into control and safety instrumentation, and startup instrumentation. Included in control and safety instrumentation are those instruments and indicators that are used for the actual control of the reactor and that have the additional function of initiating reactor scrams if a potentially dangerous condition exists in or around the reactor. The startup instrumentation is that primarily used for initial-criticality runs.

Safety and Control Instrumentation

Flux level and rate of change of flux level of the reactor are sensed by various devices in channels A through H. See Figure 7. These sensors are one fission chamber, one

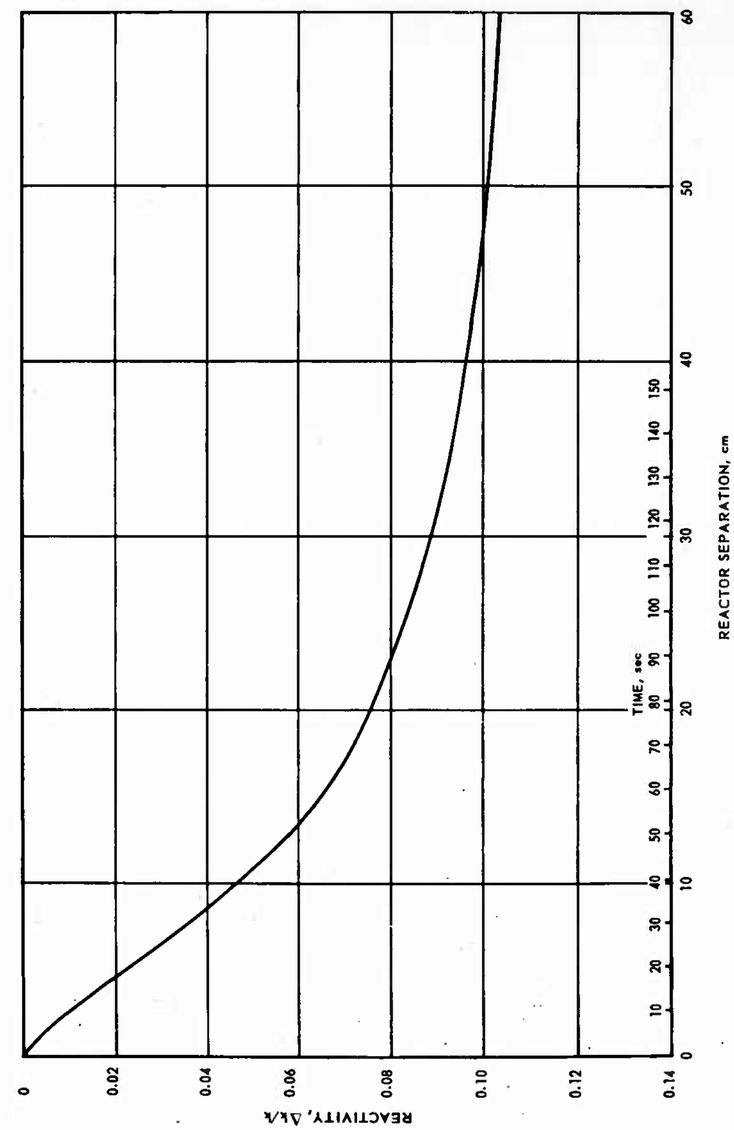

Fig. 5—Reactivity as a function of table separation and as a function of time after scram

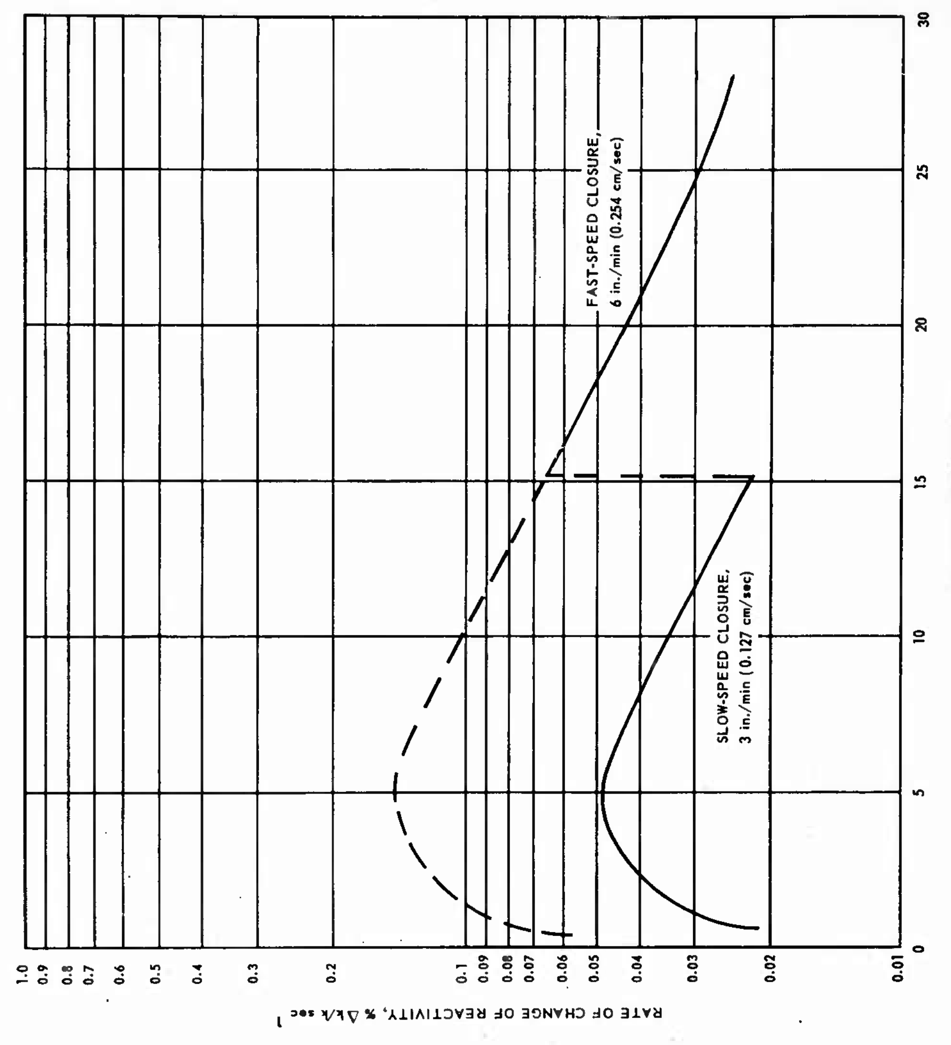

Fig. 6—Time rate of change of reactivity as a function of table separation

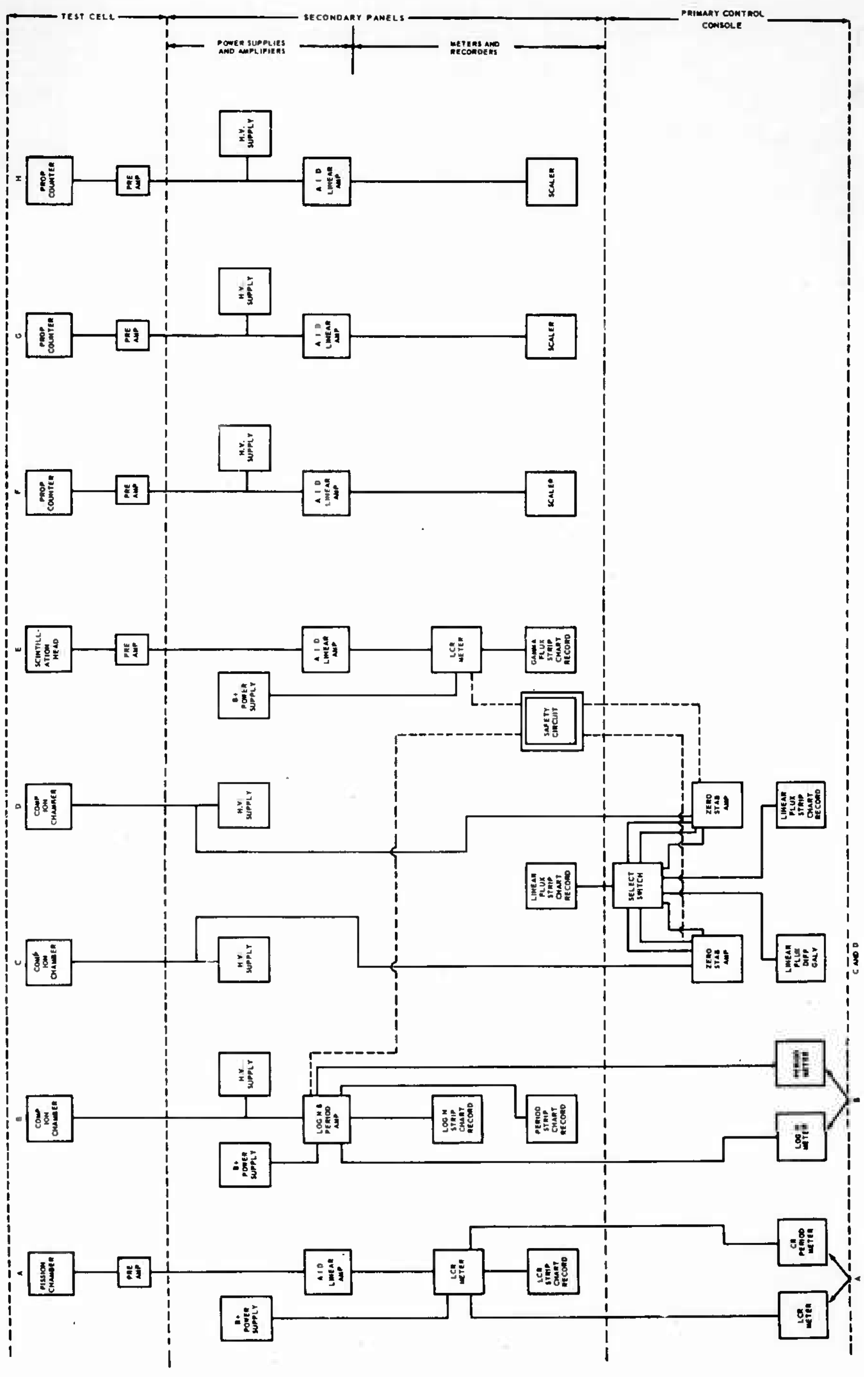

Fig. 7 – Block diagram of nuclear channels

scintillator, three compensated ion chambers, and three proportional counters. The signals from these sensors are amplified and used to operate scalers, meters, recording circuits, and scram circuits situated in the control-room primary and secondary panels.

Channel A, Log Count Rate and Period - This channel operates from a U^{235} fission chamber placed adjacent to the reactor. The signal is preamplified and then amplified by an A-1-D amplifier situated on the secondary panels in the control room. The amplified signal goes to a log-count-rate meter and a 5-decade log-count-rate recorder. The signal also goes to a log-count-rate meter and count-rate-period meter situated in a panel of the primary control console.

Channel B, Log Flux and Period - Channel B operates from a compensated ion chamber. The signal is amplified by a log-N and period amplifier situated in a cabinet of the secondary panel. Also situated in this cabinet are one 6-decade log-N strip-chart recorder, one -30-second to +3-second period recorder, and one B+ power supply. These indications are repeated on the primary console by a log-N meter and a period meter. This channel operates a period scram in the safety circuitry.

Channels C and D, Linear Flux - Channels C and D both operate from compensated ion chambers. The signals are amplified by zero-stabilized amplifiers. A selector switch is provided to place the signal from either amplifier on a 0-to-110-percent linear-flux strip-chart recorder in the secondary panels. This signal is further transmitted to a linear-flux-difference galvanometer and linear-flux strip-chart recorder. These channels each operate a level scram in the safety circuitry.

Channel E, Log Count Rate (Gamma) - Channel E uses a scintillation head, the signal from which is preamplified and then amplified by an A-1-D amplifier and directed to a 6-decade gamma log-count-rate meter and strip-chart recorder situated in the secondary panels. This channel provides a high-level scram in the safety circuitry.

Startup Instrumentation

Channels F, G, and H, Proportional Counters - These channels are identical and consist of proportional counters whose signals are preamplified and then amplified by A-1-D amplifiers and directed to scalers in the secondary panels. These channels are not included in the safety circuitry, but will serve as aural monitors and indicators of subcritical multiplication.

Primary Console

The panel arrangement of the primary console and secondary panels is shown in Figure 8. Starting with the left panel on the primary console, these panels are described below.

Left Console Panel - This panel contains two zero-stabilized amplifiers for linear-flux-channels C and D. Each of these amplifiers has meters indicating linear flux from 0 to 110 percent, range-selector switches, normal power switches, and indicator lights. Either of these amplifiers may be switched to operate the linear-flux strip-chart recorder and meter in the secondary panel, and the strip-chart recorder on the primary console.

The left panel also contains a key-operated Reactor Operate switch, reactor On and Off lights, and a Scram Reset switch.

Center Console Panel - This panel contains the primary meters by which the reactor is brought up to power and controlled. This instrumentation includes a difference galvanometer for channels C and D, log-N and log-N-period meters for channel B, and the count-rate meters for channel A.

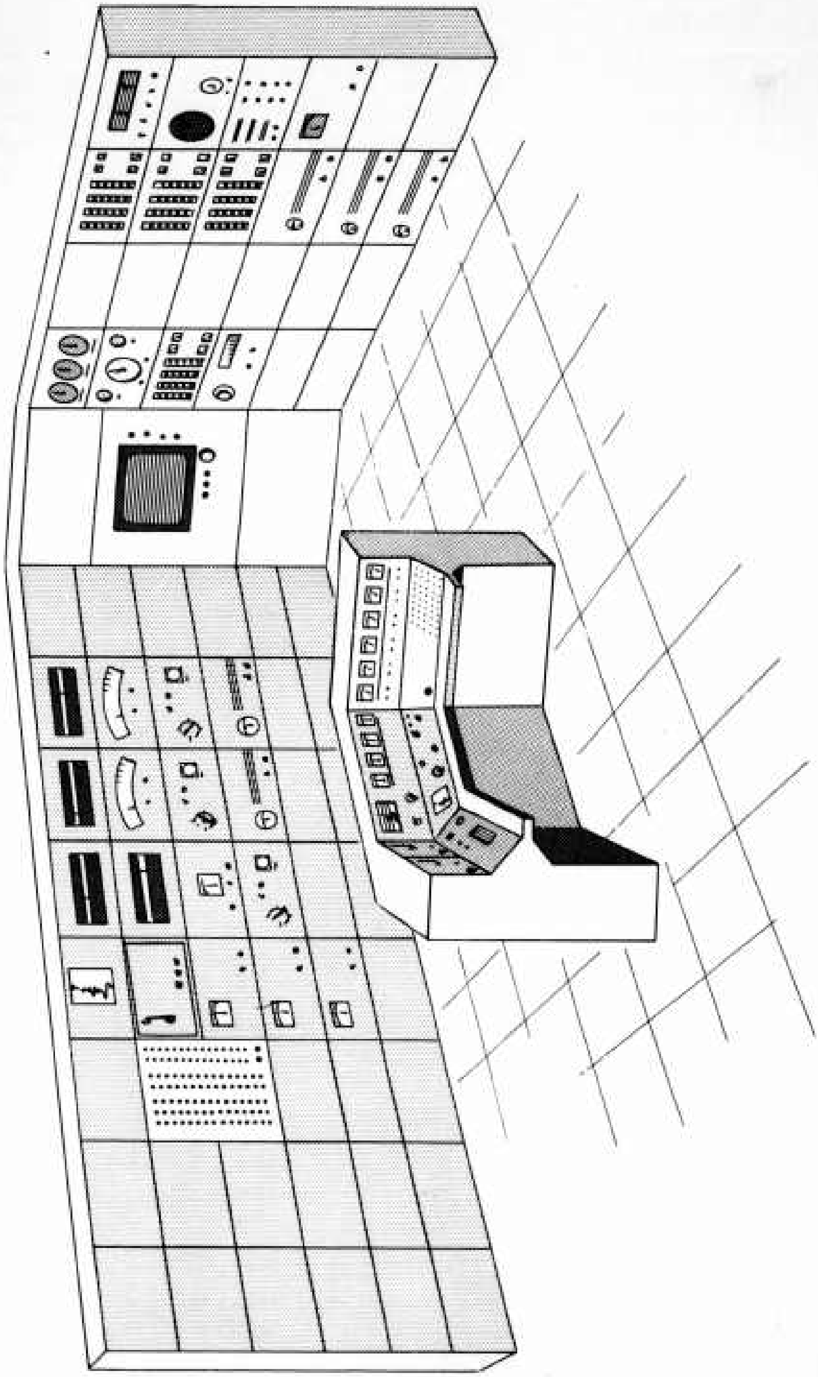

Fig. 8 – Control console

The center panel also includes the following controls and instrumentation: linear-flux strip-chart recorder, frame-selector switch, shutdown switch, source-rod control switch, and position-indication lights for the source rod.

Right Console Panel - This panel includes the actuator position indicators and selecto switches. Power to the individual actuators is provided by a versatile switching system through which six or less actuators can be moved simultaneously. The selection of actuators is made first through a frame selector switch and then through six pairs of actuator switches. The actuator switches are only energized if the frame selector switch is in position 1. Each pair of actuator switches provides the means of selecting any or no actuators. Five additional positions are provided on the frame selector switch. Each of these positions can in turn energize up to six preselected actuators connected at the patch panel.

Secondary Panel

The secondary console contains the necessary amplifiers, power supplies, scalers, strip-chart recorders, etc., necessary for operation of the various channels of instrumentation outlined in the preceding sections. In addition, the following instrumentation is also in the secondary panels.

Rod-Position Scanner - This instrument consists of a digital ratiometer, scanner, and typewriter. At any desired time the position of all control rods can be printed out by the typewriter. In addition, the position of a single rod can be followed for accurate positioning.

Period Calibration - Signals taken from the fission chamber channel or from one of the proportional counters will be used for accurate period measurements.

Television - A television receiver and appropriate control equipment will be used for viewing the test cell at all times.

Extra Panels - Several extra panels are available for use in checking out special equipment, for mounting shielding instrumentation, and for other control instrumentation, such as heating controls.

2.4 OPERATION OF THE REACTOR

2.41 GENERAL OPERATING PROCEDURE

The following general rules will be followed in the normal operation of the HOTCE.

1. The reactor will not be operated with less than two qualified operators present in the control room. One man will have complete control of the operation at any one time.
2. At the beginning of each operating period, each instrument will be checked with a source and each control rod will be cocked and fired to insure correct operation.
3. Before any operation is begun, or any alteration is made on the assembly, the operating crew must agree that the proposed procedure is safe. These decisions will be based on extrapolations from previous critical experiment data and calculations. For major alterations, the supervisor of Low Power Test Operations must also concur.
4. The log-count-rate channel must have a positive and reliable signal indication before any rods are checked or any operation is begun.
5. A preset number of control rods must be withdrawn before the assembly table halves can be joined.

6. During the approach to criticality, the period will not normally be less than 50 seconds. After criticality the period will normally be limited to not less than 15 seconds.
7. No operation will begin unless the following instruments are operative:
   a. Log-flux channel.
   b. One linear-flux channel.
   c. Gamma log-count-rate channel.
   d. One counting channel.
8. One counting channel will serve as an aural monitor for both the control room and the test cell.
9. Operations will normally be limited to less than 100 watts.
10. Access to the test cell during operations will be prevented by requiring the engineer-in-charge to personally check the test cell and to lock the test-cell doors before operations begin.

2.42 INITIAL STARTUP PROCEDURE (COLD)

The following steps will be adhered to for the initial cold approach to criticality:

1. Dry run and complete check on the operation of all instrumentation and equipment.
2. Determine the background level of the source without fuel and with the assembly table joined.
3. With the reactor tables separated and with the control rods inserted, load the central 19 fuel elements.
4. Bring the reactor table together and determine the multiplication for the following conditions:
   a. Control rods fully inserted.
   b. Control rods fully withdrawn.
5. Continue steps 3 and 4, adding 19 or less elements each time, with the requirement that an extrapolation of the reciprocal-multiplication-versus-loading curve for the rods-out condition shall not indicate a multiplication of greater than twice the last-measured rods-out value. This procedure shall be followed until less than two elements are permitted for the following loading.
6. Carefully ascertain that the available rod worth is considerably greater than the extrapolated value of two elements by a comparison of the rods-out curve with the rods-in curve.
7. Load two elements and repeat step 4.
8. Repeat step 7 until the reactor is critical.
9. After criticality is reached, fuel elements will be added one at a time and criticality achieved after each addition.
10. Fuel additions will be limited so that the worth of the control rods withdrawn at criticality is at least 2 percent $\Delta k/k$.

2.43 INITIAL STARTUP PROCEDURE (HOT)

The following steps will be adhered to for the initial hot approach to criticality:

1. With the reactor apart, load the reactor with the minimum fuel that will go critical at room temperature.
2. Determine the reactivity change versus temperature in 200°F steps until the maximum design temperature is attained.
3. No increase in reactor temperature will be permitted unless a predetermined number of control rods (estimated to be worth 2 percent $\Delta k/k$) are withdrawn.
4. Repeat step 2, and load a judicious number of fuel elements at a time.
5. Fuel addition will be limited so that the worth of the control rods withdrawn at criticality at design temperature is at least 2 percent $\Delta k/k$.

2.5 PROCESSING AND DISPOSAL OF REACTOR FUEL, FISSION PRODUCTS, AND EFFLUENTS

Contained Products

The reactor will normally be operated at approximately 1 watt for a period of 1-3 hours. For special experiments, it may be operated at slightly higher power, perhaps 100 watts, for short periods of time. Under these conditions there will be no chemical processing or disposal of reactor fission products.

Radioactive Effluents, Reactor Atmosphere

Under normal conditions of 1 watt operation, the reactor air activity from argon activation is about 2×10^{-12} curies per cubic centimeter at the close of a working period. Short periods of slightly higher operation would increase the value slightly. Since the tolerance for continuous exposure to radioactive argon is established at 5×10^{-13} curies per cubic centimeter and the halflife of A^{41} is approximately 1.8 hours, the air in the reactor following normal operation does not present a serious exposure problem. All personnel having reason to approach the reactor following operation will be briefed on all radiation hazards.

Disposal of Fuel Elements

With the low powers involved in the HOTCE operation, no processing of fuel elements will be necessary until the experiment is completed.

2.6 HOTCE SAFETY MECHANISMS

Scram Initiation

The reactor may be scrammed by any of the following systems:

1. High-flux-level scram
   A scram will occur if the neutron-flux level exceeds 1.8 times the full-scale reading of either of the linear-flux channels. A high-level scram will also occur if the gamma count-rate channel exceeds a preset level (normally about 100 watts).
2. Period scram
   A scram will occur when the period as determined by the log-flux channel decreases below a preset value (normally set at about 10 seconds).
3. Manual scram
   The initiation of a scram may be made by depressing the scram button located on the control console.
4. Power Failure
   A scram will be initiated by loss of general power.

Scram Action

1. Results
   When a scram signal is received, the following action will result.
   a. All control rods will be fired.
   b. Table halves will separate.
   c. The air-conditioning system will be shut down in the CE cell.
2. Action of Control Rods
   The rods will fire when the current flowing in the magnet coil is interrupted. For all scram signals, the magnet circuit is interrupted and the rod is fired within 150 milliseconds.
3. Action of Table Separation
   The table halves separate at a minimum velocity of 6 inches per minute, regardless of the starting position.

Scram Reset

After a scram has been initiated, return to normal operating conditions will be attained by depressing the scram reset switch after the cause of the scram has been cleared.

Interlocks

A system of interlocks is provided as follows:

1. Control rods can be withdrawn only if the flux level is greater than a preset minimum and if the period is greater than some preset level (about 15 seconds).

2. The CO_2 flooding system must be in manual position before the scram bus can be cleared.

Other Safety Features

1. All operating switches move to the left to decrease reactivity and to the right to increase reactivity. This is the same direction as the motion of all instruments. Switches are spring-loaded to return to their neutral position after motion.
2. No provision is made for bypassing interlocks.
3. Only one frame of rods may be moved to a more reactive position at a time, but all rods may be moved simultaneously to a less reactive position.
4. All relays will be wired so that power failure will produce a safe condition in the reactor.

3. HAZARDS

3.1 RISKS MINIMIZATION

Further steps taken to minimize the risks of operating the HOTCE are listed under the following headings of Security Measures and Safety Measures:

1. Security Measures
   - a. The HOTCE will be operated in the Low Power Test Facility, an exclusion area located a mile southeast of the Idaho Test Station.
   - b. All personnel legally entering the area must have been granted special permission in addition to a "Q" clearance prior to their visiting or working in the LPTF. The mechanics of this procedure will be the same as for other exclusion areas at the ITS.
   - c. During working hours there will be a guard on duty at the main entrance to the area. There is only one entrance and exit to the area. During nonworking hours there is a security guard patrolling the building and area. In addition, the test cells are sensitized against entry by a sonic alarm connected to the main American District Telegraph system.
   - d. The door to the SS material storage vault will be security alarmed at all times. Permission to open the safe must be obtained from the security control center.
   - e. The doors to the test cells are equipped with a key lock.
2. Safety Measures
   - a. Scram mechanisms and reactor-table separation are provided to bring the reactor well below critical if the flux levels rise above normal values. In addition, airflow to the test cell is stopped.
   - b. A number of interlocks are incorporated to guarantee safe startup and normal operating procedures.
   - c. Written procedures will apply to startup and normal operations, minor changes in reactor geometry or composition, and emergency conditions. Daily checks will be made of proper placement of units, operation of important mechanisms, and operation of the health-monitoring system.
   - d. Large lighted signs that indicate reactor On or Off are placed in strategic positions. There is extensive use of signal lights to remind the operation of conditions having an important bearing on operations. An aural monitor will be in the test cell and control room.
   - e. Equipment has been designed to be fail safe.
   - f. Only one mechanism for increasing reactivity can be operated at a time.

3.2 POTENTIAL CAUSES OF NUCLEAR INCIDENTS

Various means of initiating reactor runaways have been considered. Generally, these fall into two broad classes, accident and sabotage. Accidents are defined as incidents resulting from human error or equipment failure. Sabotage involves tampering with intent to cause damage, physical or phychological.

Accident-wise, this assembly is very safe. Careful examination reveals that multiple equipment failures and in most cases some degree of negligence must take place to have an accidental reactor runaway.

As with any other facility, this one is susceptible to sabotage if preventive security measures are bypassed.

For an accident to occur, at least two things must happen. First, the reactor must be put into a critical or near-critical condition, i.e., "set up" for the accident, and then a fast-acting initiating mechanism that would make the reactor supercritical must be introduced. Below are listed the mechanisms that, if they occurred, could either set up the reactor or serve as initiating mechanisms.

Setup Mechanisms

1. Move reactor halves together.
2. Add end or side reflector.
3. Add extra fuel to the core (very unlikely as an accident).
4. Leave poison out of the core.
5. Add moderator to a fueled region.
6. Have a failure of the control, safety, table, or instrument systems.
7. Change core temperature.

Initiating Mechanisms

1. Move reactor halves together.
2. Add moderator to the fueled region.
3. Compact the core.
4. Remove poison from the core.
5. Force control and safety assemblies rapidly out of the core.
6. Change core temperature.

Closing the reactor halves could serve either as a setup or as an initiating mechanism. As an initiating mechanism, the halves could close with their normal speed sequence or they might move uncontrollably at their maximum speed of 6 inches per minute. The latter requires failure or sabotage of the table-drive-motor control mechanism, as well as the reactor being rendered unresponsive to a scram signal.

Compacting of the core is possible only as an act of sabotage; and even if sabotage were attempted, there is every indication that it would not be successful in causing an incident.

Analysis of the various means of initiating reactor runaways has shown that the maximum accident could be caused by a potentially critical reactor being made supercritical by joining of the table halves. Sabotage could be accomplished by several different methods of initiating incidents, but nearly all of them require a similar sequence of events: i.e., manipulation of control and safety systems to make them inoperative or to operate in a way that would enhance an incident, or a critical or near-critical reactor and an initiating action such as driving poison out of the reactor, bringing the table halves together, or adding fuel or a good moderator to the fuel-air region.

3.3 RUNAWAY ANALYSIS

The general methods of analysis used to calculate the results of reactor runaways were previously developed in conjunction with hazard studies on another direct-air-cycle reactor.* A summary of these methods is presented here along with the results of the calculations, a comparison of the runaways, and a correlation of the physical events causing the runaways. From the calculations, the events inside the reactor and the amounts of energy and fission fragments ejected from the reactor as a result of the runaway can be evaluated.

3.31 METHODS OF CALCULATION

The reactor runaway calculation described below has been programmed for the IBM 704 digital computer.

Above-prompt-critical runaways for the HOTCE reactor are analyzed in two stages, (1) from the start of the runaway until vaporization of fuel elements begins and (2) vaporization of fuel elements and their expulsion from the reactor. The latter stops the runaway. During the first stage of the runaway the power level rises exponentially (assumed to start at 10 watts) until the energy produced equals 4.56×10^5 kilowatt-seconds. At this point vaporization of the fuel element begins, and the vapor is expelled from the reactor by the subsequent pressure buildup. This loss of fuel from the reactor decreases the reactivity and stops the runaway.

The First Stage - Before Fuel Elements Vaporize

For mathematical convenience, each runaway is assumed to be initiated by a simple, discontinuous increase (step change) in reactivity. The effect of delayed neutrons is neglected, and no temperature coefficient of reactivity is introduced. An analytic (exponential) solution is obtained for this idealized case. In the next step, the analysis of the runaway, the assumptions are made that the reactivity increases linearly with time and that the contribution to energy due to the delayed neutrons is constant. The runaway induced by the linear change in reactivity is then said to be equivalent to a runaway induced by a step change in reactivity when each results in the same period at the start of fuel element vaporization. It thus is possible to interpret the calculations in terms of the time rate of change of reactivity involved in the physical event causing the accident, even though the actual calculations are completed by assuming a step change in reactivity.

The Second Stage - Vaporization of Fuel Elements and Shutdown of the Reactor

Vaporization of the fuel elements and shutdown of the reactor are analyzed by means of the characteristics listed below.

1. The reactor is characterized by a certain power-density distribution so that if q is the power density in fraction of total power per unit mass of fuel element, then $M(q)dq$ is the mass of fuel elements that have a power density between q and $q + dq$ and $qM(q)dq$ is the fraction of total power in those fuel elements having power densities between q and $q + dq$.
2. The fuel element vapor is distributed uniformly inside the reactor.
3. The temperature through the fuel elements is constant.
4. Fuel elements that are undergoing vaporization have the same temperature as the fuel element vapor. This temperature is determined by a Clapeyron-type equation.
5. The solid fuel elements inside the reactor have only internal energy.
6. The vaporized fuel elements inside the reactor have kinetic energy as well as internal energy. Also, after the fuel elements vaporize, they expand to a pressure P and a volume of $1/\rho$ (ρ = density) per unit mass; thus, a unit mass of fuel element does work in expanding equal to P/ρ.
7. The vapor that has flowed outside the reactor has internal energy, kinetic energy, and does flow work on the gas outside. The gas flow rate out of the reactor is determined by the equations for adiabatic flow of a perfect gas through a nozzle.

*The reports listed below have been issued on previous hazards evaluations:

G. P. Kerr, "Summary Hazards Report for Zero Power Tests with the R-1 Mockup Reactor," APEX-110, ANPD, October, 1952.

C. C. Gamertsfelder, "HTRE Hazards Report," APEX-180, ANPD, December 15, 1954.

F. W. Mezger, "Analysis of LPT and ZPT Reactor Runaways," APEX-213, ANPD, December 30, 1955.

8. No fuel elements vaporize until the fuel element temperature is high enough to maintain vaporization under 1 atmosphere of vapor pressure.
9. The runaway is stopped by fuel element vapor leaving the reactor. The resulting decrease in reactivity is assumed to be proportional to the total vapor flow out.

3.32 COMPARISON OF RUNAWAYS RESULTING FROM VARIOUS REACTIVITY INCREASES

The characteristics of the runaways are best interpreted graphically. Figure 9 shows the number of fission fragments produced and the number ejected as a function of step change in reactivity. Figure 10 shows the total energy developed in the runaway as a function of step change in reactivity.

Maximum power level in a runaway as a function of step change in reactivity is shown in Figure 11.

Figures 12 and 13 show, respectively, the maximum temperature and the maximum pressure of fuel element vapor as a function of step change in reactivity.

Figures 14 and 15 show, respectively, the power level and time at which vaporization of fuel elements begins as a function of step change in reactivity.

Figure 16 gives the step change in reactivity that is equivalent to a given linear increase in reactivity.

3.33 CORRELATION OF PHYSICAL EVENTS CAUSING RUNAWAY WITH REACTIVITY INCREASES

Maximum-Speed Table Closure

Reactivity is added at its maximum rate at a table separation of about 5 centimeters. At a table speed of 6 inches per minute the linear rate of reactivity increase would be about 0.14 percent $\Delta k/k$ per second, an amount corresponding to a step change of only slightly less than 1 percent $\Delta k/k$. Of course, it must be assumed that the reactor goes critical at the 5-centimeter separation and that simultaneously the table-drive-motor control mechanism and scram system fail.

Normal-Speed Table Closure

If it is assumed that the reactor is critical at a table separation of about 5 centimeters, the normal closure rate of 3 inches per minute gives a linear rate of reactivity increase of 0.07 percent ($\Delta k/k$) per second. Since this runaway will be roughly equivalent to one initiated by a prompt-critical step change, a method of analysis differing from that described above was used. This method is derived in KAPL-646 and discussed on pages 10-12 in APEX-213. It provides, on the basis of an analytical solution of the reactor kinetic equations, a relationship among reactivity, flux, and delayed-neutron concentration for two different times during the runaway. Specifically, if the reactivity responsible for the runaway and the flux and delayed neutron concentration at the time fuel element vaporization begins are known, the reactivity of the assembly after the accident can be determined. From this reactivity the mass of fuel elements vaporized and ejected can be found.

Sabotage

Provided a saboteur can bypass all security measures taken to prevent his access to the test cell, sabotage could be accomplished in a number of ways. His success would depend upon his imagination and intelligence. No attempt is made to identify a most probable sabotage or a worst possible sabotage.

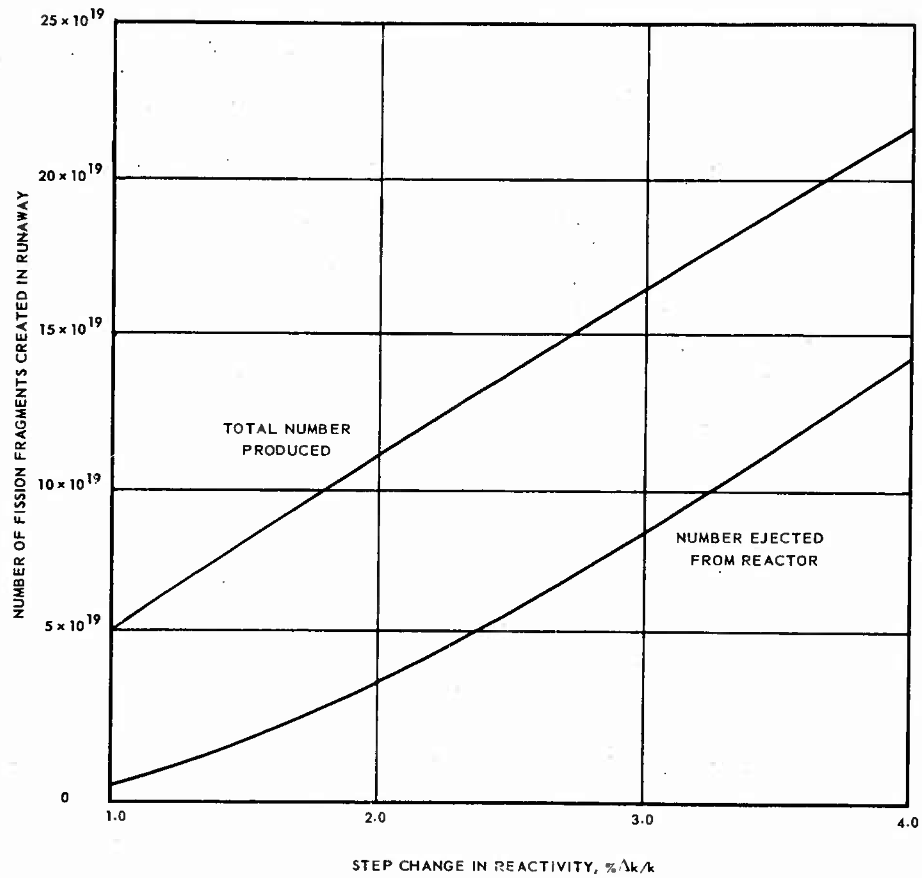

Fig. 9 — Number of fission fragments produced as a function of step change in reactivity

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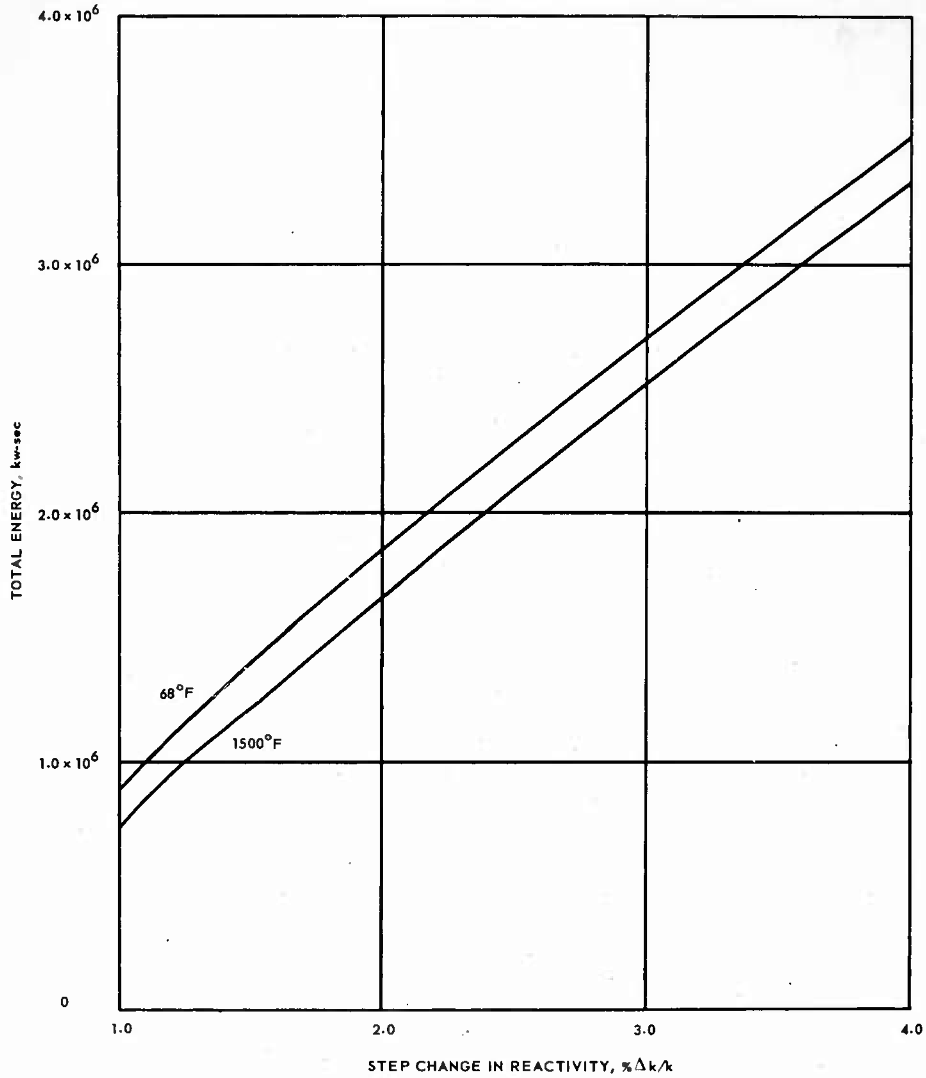

Fig. 10 — Total energy developed in a runaway as a function of step change in reactivity

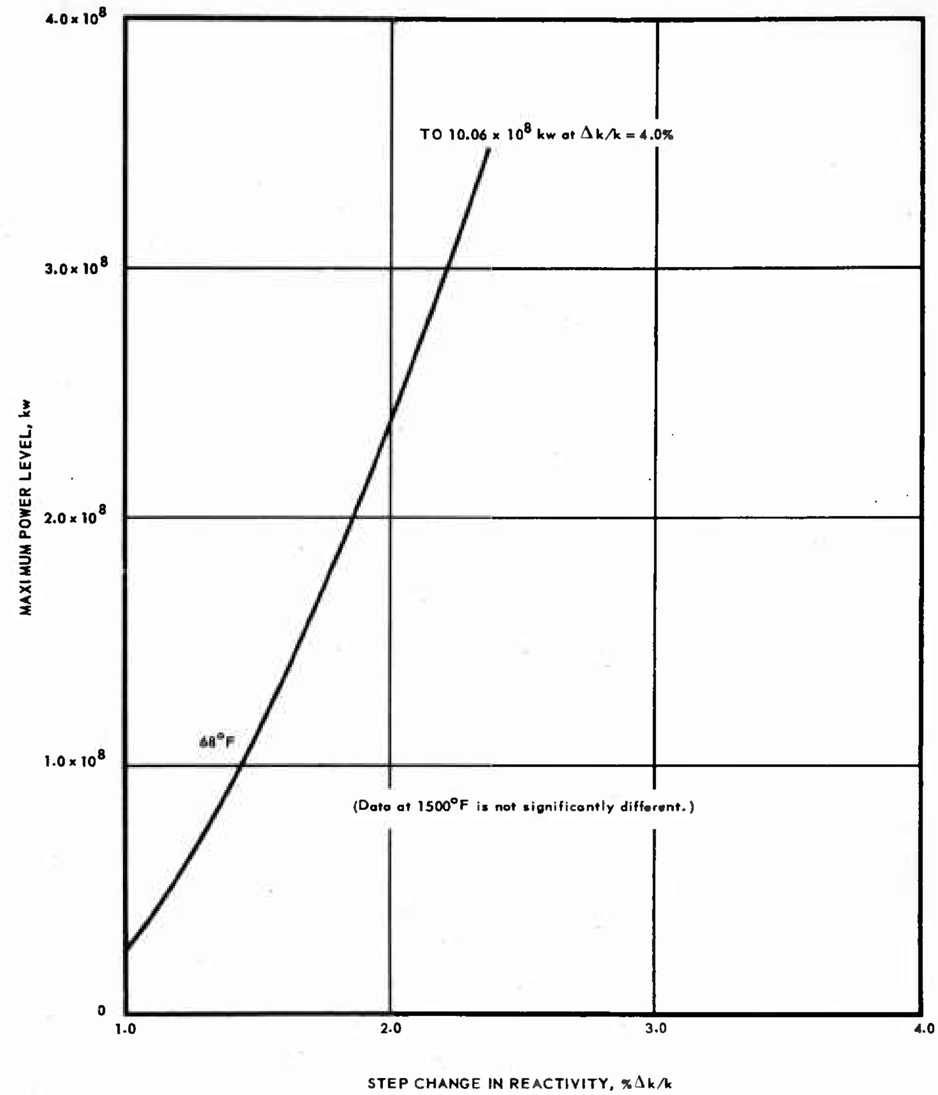

Fig. 11 — Maximum power level attained during runaway as a function of step change in reactivity

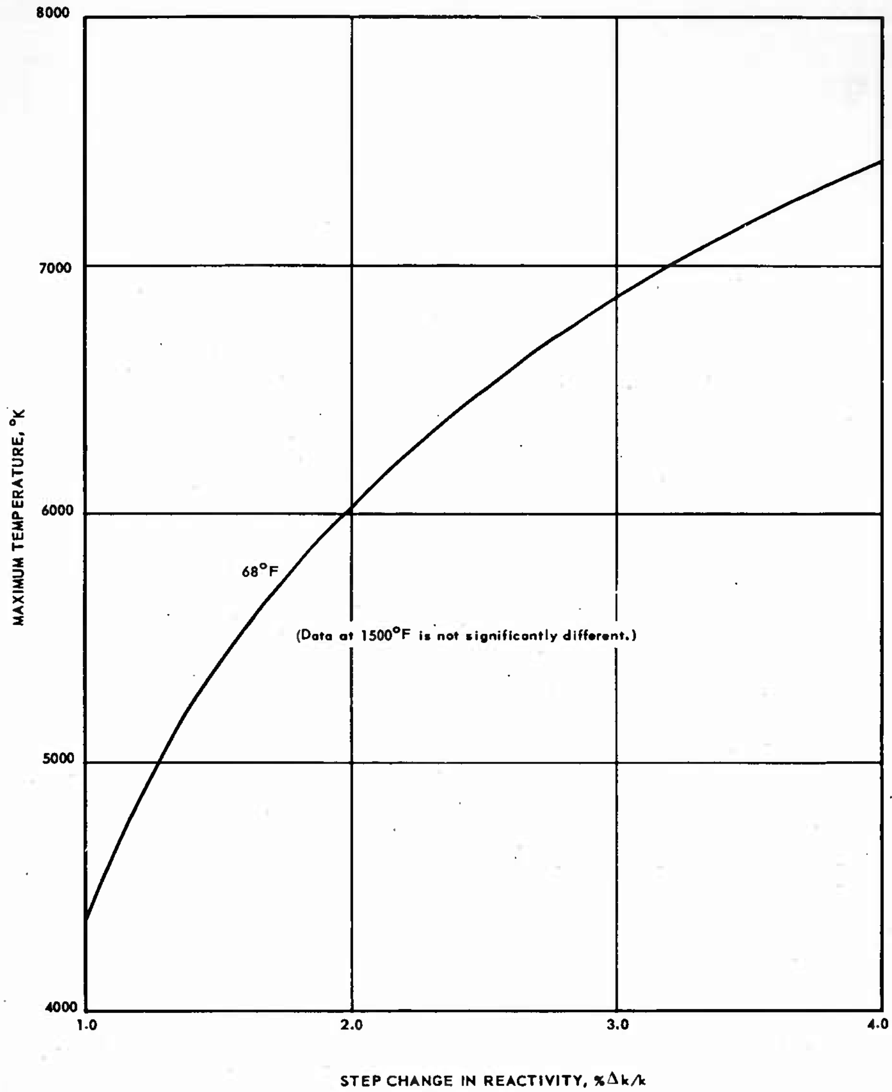

Fig. 12 – Peak temperature of fuel element vapor inside reactor as a function of step change in reactivity

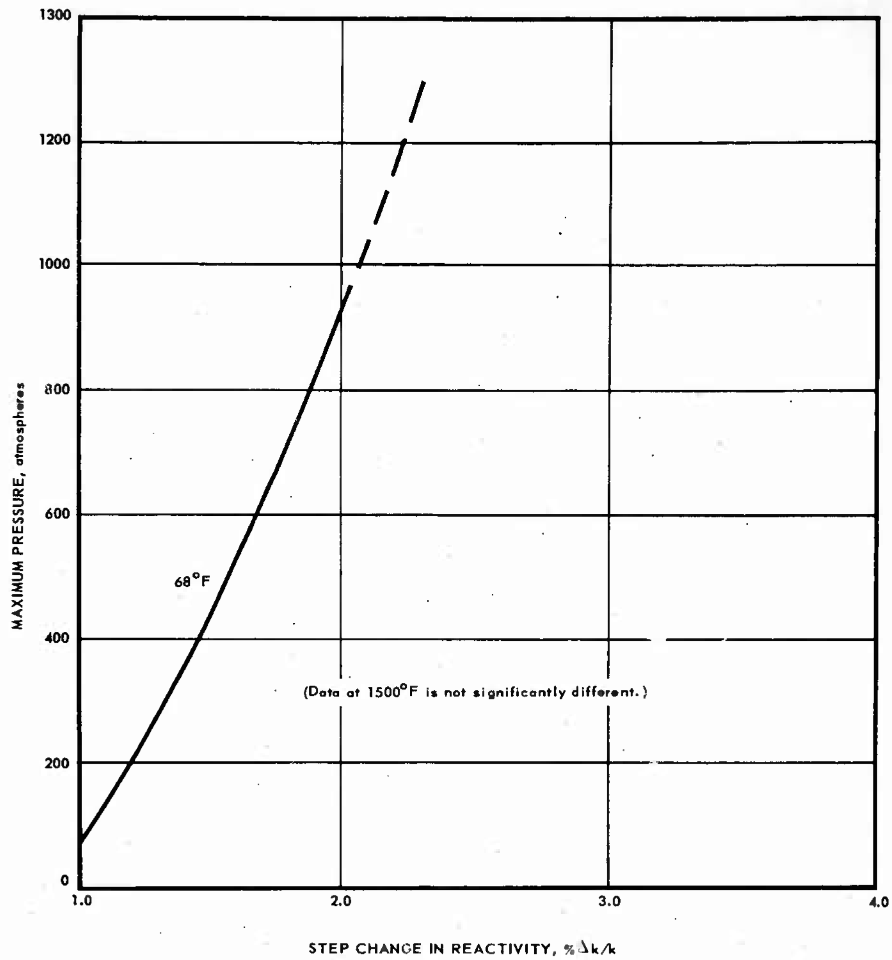

Fig. 13 – Peak pressure of fuel element vapor inside reactor as a function of step change in reactivity

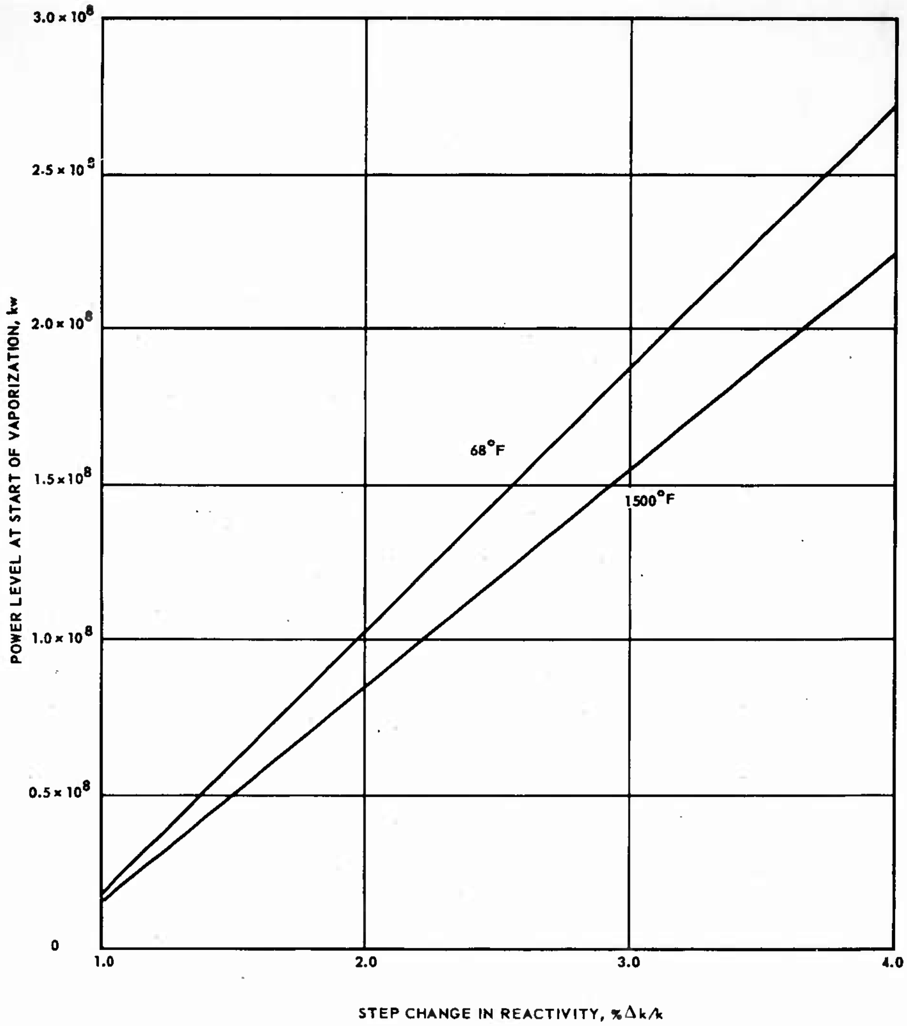

Fig. 14 — Power level at start of vaporization of fuel elements as a function of step change in reactivity

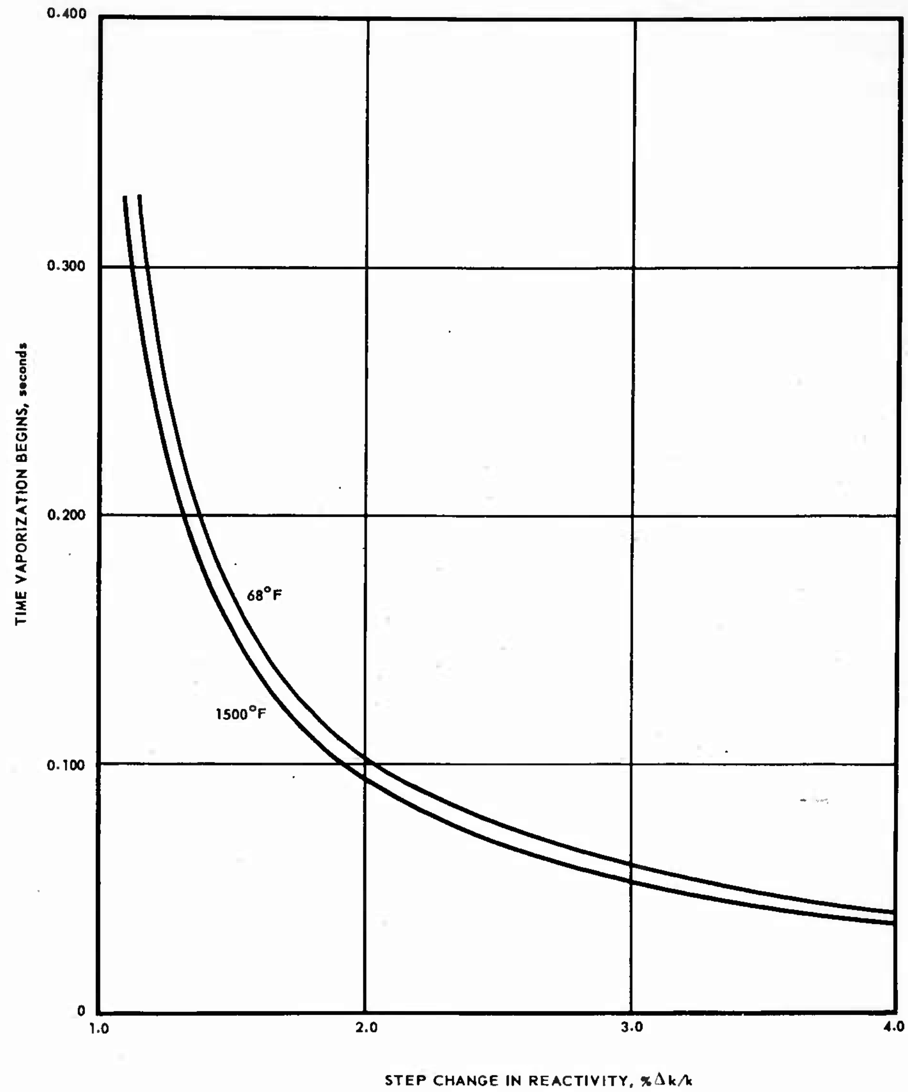

Fig. 15 – Time at which vaporization of fuel elements begins as a function of step change in reactivity

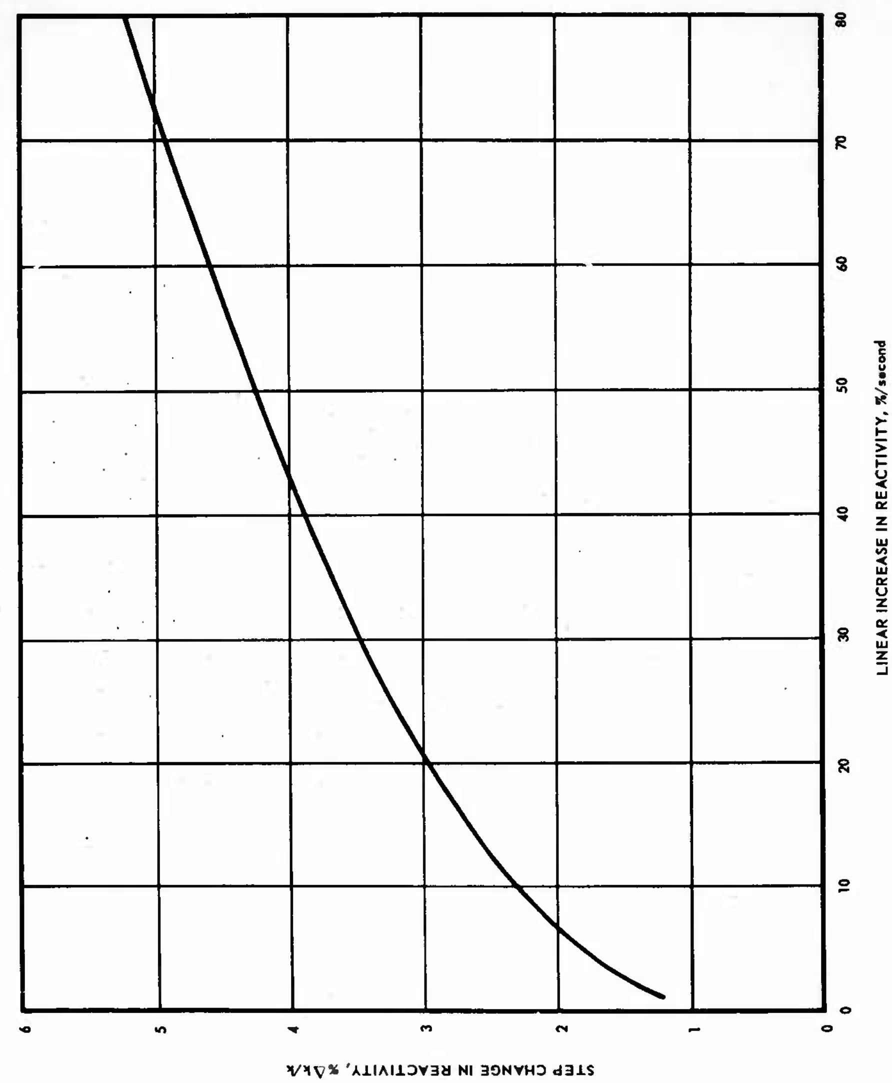

Fig. 16—Step change in reactivity equivalent to a linear increase in reactivity

SUMMARY OF RUNAWAY CALCULATIONS

Initiating Mechanism	Fast Table Closure	Normal Table Closure
Step $\Delta k/k$	0.0096	0.0077
Maximum core pressure, atmospheres (absolute)	70	~1
Total fission energy, kw-sec	8.9×10^5	6.1×10^5
Fission fragments created	5.5×10^{19}	3.8×10^{19}
Fission fragments ejected from core	0.56×10^{19}	0.31×10^{19}

3.4 IMMEDIATE RESULTS OF ACCIDENTS

The maximum accident is taken to be high-speed table closure with the assembly reaching criticality at a 5-centimeter separation. The most credible accident is of the same type, except that the tables are assumed to close at their normal rate.

3.41 DIRECT RADIATION DOSAGE RESULTING FROM MAXIMUM ACCIDENT

The runaway resulting from the maximum accident releases 8.9×10^5 kilowatt-seconds in fission energy. The greatest dosage that could be received outside the test cell from this release would be approximately 3 rem.

3.42 ENERGY AND MASS RELEASED TO TEST CELL

During and immediately following the runaway, quantities of the following will be expelled from the reactor:

1. Fission fragments
2. Fuel element vapor
3. U_3O_8 and UO_2
4. Activated argon.
5. C^{14} from the $N^{14}(n,p)C^{14}$ reaction.
6. Heat of oxidation and kinetic energy of fuel element material.

The heat energy released in an accident during which fuel elements vaporize and are ejected from the reactor will bring about an increase in the temperature of the atmosphere in the test cell. In an accident in which all the fuel elements were vaporized and ejected, about 16×10^5 kilowatt-seconds would be liberated in combustion of the material. For the table-closure accident considered previously, with ejection of about 1/10 of the fuel elements, the temperature rise in the cell would be about 100°C and a pressure increase of about 1/3 atmosphere would result. Such a pressure rise would blow out the test-cell door and release the radioactive products of the excursion to the atmosphere. Doses produced by the release of this material are discussed in the next section.

4. HAZARDS TO SURROUNDING AREA

4.1 POSSIBLE EXPOSURE OF SURROUNDING AREA

The largest calculated doses to downwind inhabitants are due to fallout and rainout. These have been calculated on very pessimistic assumptions, and indications from actual IET experience are that ground deposition will not be a controlling hazard. The calculations that will be used as a basis for control are based on doses to individual critical organs. The most important critical organs are: the thyroid, because of the iodines; the lung, for the case in which the effluent is insoluble; and the bone, if the bone-seeking elements are soluble. The actual largest calculated doses are for the thyroid, but the relative hazard to the thyroid is probably less than that to the lung or bone because of its comparative radiation resistance. Methods of calculating doses will be given for all three organs.

The following calculations are based on a modification of Sutton's diffusion equations and on the behavior of inhaled materials as defined in *Handbook 52* of the US Bureau of Standards.

If the number of curies of a particular isotope emitted is C and the person inhaling this material breathes at the rate of R m^3/sec, the amount breathed into the lungs is

$$A = \frac{2RCe^{-\lambda t_e}}{\pi u h^2} f(\sigma, h, h') \text{ curies,}$$

in which

$$f(\sigma, h, h') = \frac{h^2}{\sigma^2} \sum_{m=0}^{\infty} \left[e^{-\left(\frac{2mh' + h}{\sigma}\right)^2} + e^{-\left(\frac{2(m+1)h' - h}{\sigma}\right)^2} \right]$$

The various quantities in these expressions are defined as follows:

$\sigma = cx^{1-n/2}$

x = downwind distance, m

c = virtual diffusion coefficient, $m^{n/2}$

n = dimensionless stability parameter

h = height of emission point, m

h' = height of inversion layer, m

u = wind velocity, m/sec

λ = disintegration constant, sec^{-1}

t_e = time since emission that inhalation takes place, sec

[redacted]

The dose rate to the organ involved at the time t is:

$$\frac{dD}{dt} = \frac{f_a A (3.7 \times 10^{10})(1.6 \times 10^{-6})\,\overline{E}}{100\, f_c\, g}\, e^{-\lambda_e (t - t_e)}\ \frac{\text{rads}}{\text{sec}}$$

where

f_a = fraction of inhaled material that reaches organ

$\overline{E}$ = effective energy of radiation, Mev

f_c = fraction of organs available (= 0.2 for bone, = 1 for others)

g = mass of organ, grams

λ_e = effective elimination constant $(\lambda + \lambda_b)$

λ_b = biological elimination constant, sec^{-1}

The total dose to the critical organ from time of inhalation to infinity is then, assuming

$$R = 3.47 \times 10^{-4}\ \text{m}^3/\text{sec}\ (10^8\ \text{m}^3\ \text{per 8 hr}),$$

$$D = 0.131\ \frac{C f_a \overline{E}\, e^{-\lambda t_e}}{f_c\, g\, \lambda_e} \cdot \frac{f(\sigma, h, h')}{u h^2}\ \text{rads}.$$

For a fission product isotope generated in a reactor that operated at a power P_0 for T seconds, there would be a total of

$$C = \frac{3.22 \times 10^{10}}{3.7 \times 10^{10}}\, P_0\, \gamma\, (1 - e^{-\lambda T})$$

$$= 0.872\ W \gamma \lambda\ \text{curies}$$

where

γ = fission yield of isotope

F = fraction of fission products formed that are emitted

W = energy of runaway in joules

Now the dose becomes

$$D = 0.114\ \frac{F W f_a \overline{E}\, \gamma \lambda\, e^{-\lambda t_e}}{f_c\, g\, \lambda_e} \cdot \frac{f(\sigma, h, h')}{u h^2}\ \text{rads}.$$

If the same fractional amounts of a number of different isotopes that all go to the same organ are emitted, then

$$D = 0.114\ F W \sum \frac{f_a \overline{E}\, \gamma \lambda\, e^{-\lambda t_e}}{f_c\, g\, \lambda_e} \cdot \frac{f(\sigma, h, h')}{u h^2}\ \text{rads}.$$

Curves of

$$\sum \frac{f_a \overline{E}\, \gamma\, \lambda_e^{-\lambda t_e}}{f_c\, g\, \lambda_e}$$

are plotted against t_e for each of the organs in Figure 17.

[redacted]

[redacted]

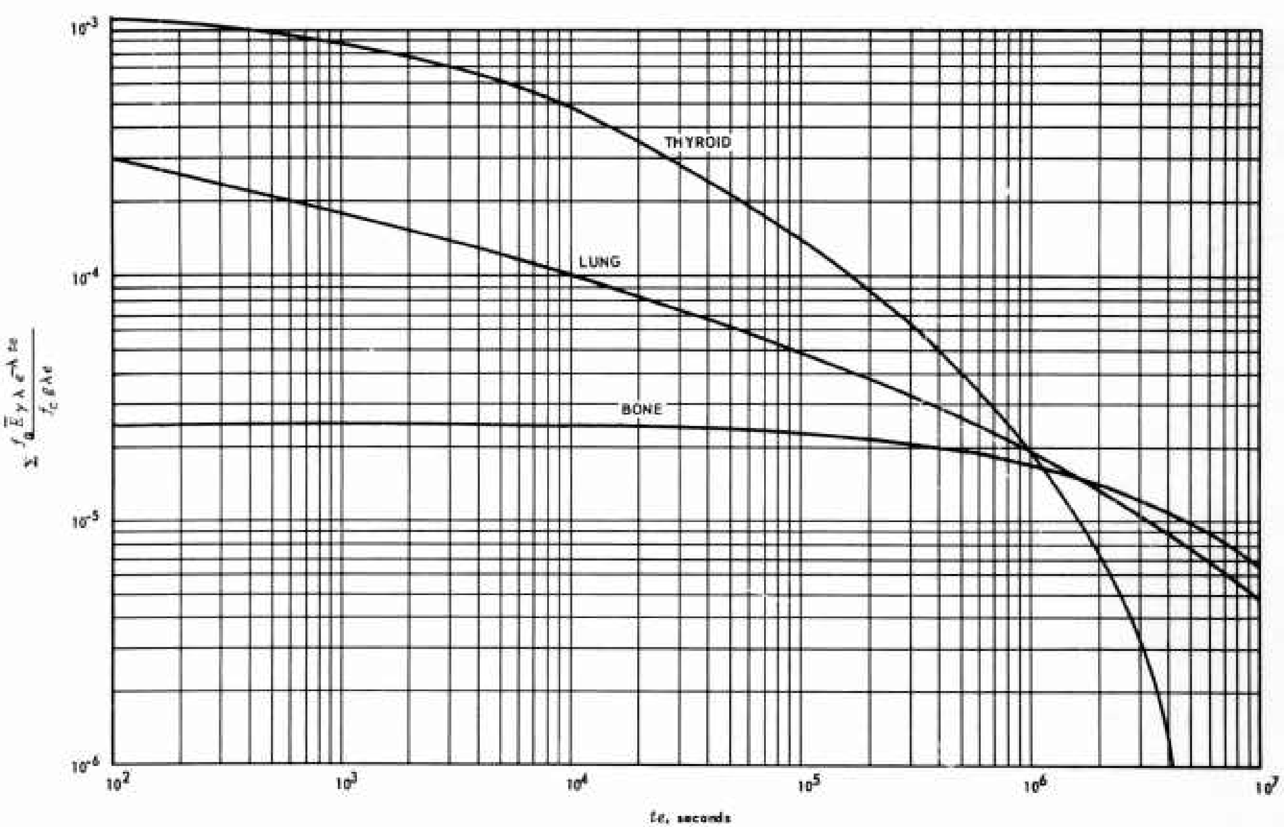

Fig. 17 – Isotopic summation $\left(\Sigma \frac{f_a \bar{E} \gamma \lambda e^{-\lambda t_e}}{f_c g \lambda e} \right)$ versus time (t_e) since emission for thyroid, lung, and bone

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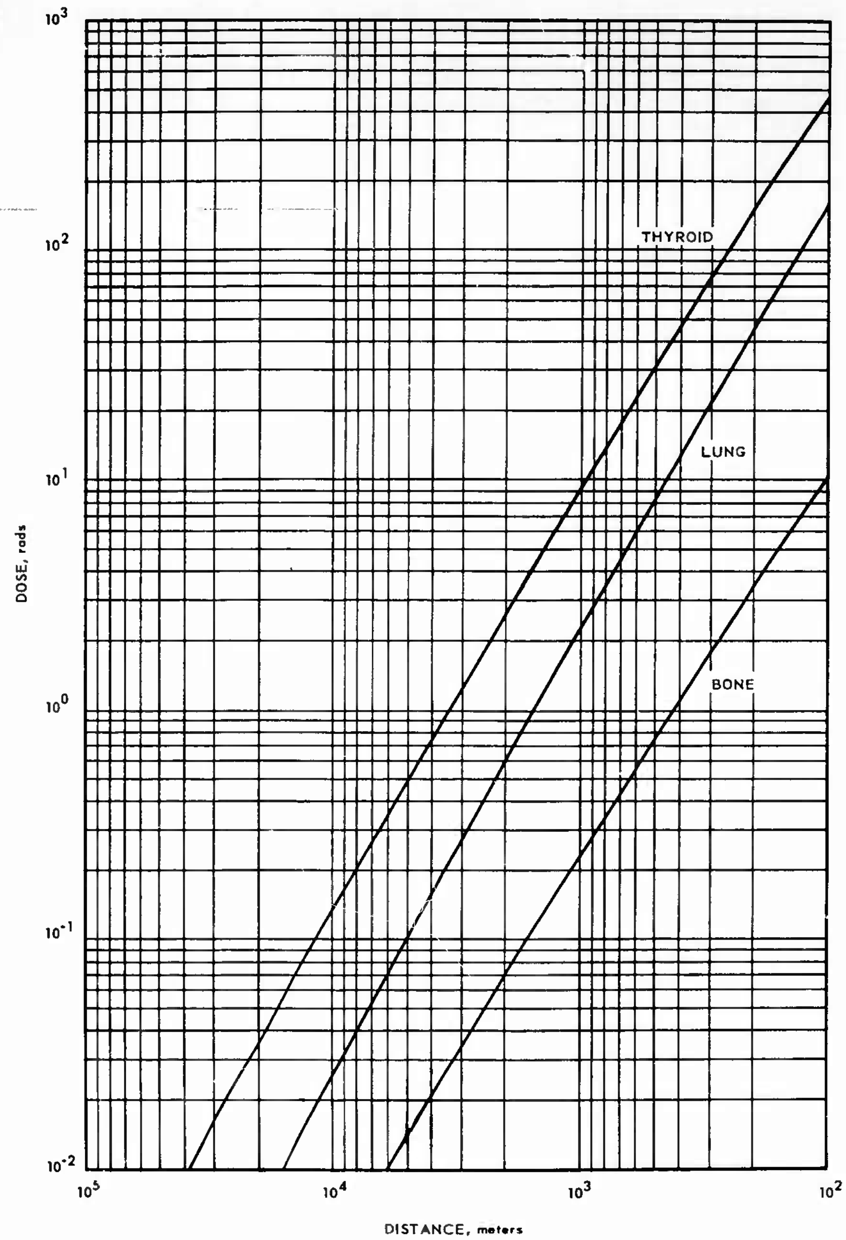

Fig. 18 – Dose versus distance for emission of 10 percent of fission products in an accident producing 8.9×10^8 joules of energy

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In Figure 18 are plotted the doses that would be received by the thyroid, lung, and bone at various distances from the point of emission of the fission products. The doses correspond to the table closure accident described above in which 8.92×10^8 joules of fission energy are produced and 10 percent of the fuel elements are vaporized, ejected, and released to the surround atmosphere.

The atmospheric conditions assumed are described by the quantities:

$n = 0.333$
$h = 0$ (effective height of emission)
$u = 3$ m/sec (wind velocity)
$c = 0.06$
$h' = \infty$ (inversion layer infinitely high)

When $h' \to \infty$, the expression $\dfrac{f(\sigma, h, h')}{u\, h^2}$

reduces to $\dfrac{e^{-h^2/\sigma^2}}{u\, \sigma^2}$.

4.2 HYDROLOGY AND GEOLOGY OF THE NRTS AREA*

4.3 METEOROLOGICAL DATA*

5. MAKEUP OF SURROUNDING AREA*

5.1 POPULATION DISTRIBUTION OF THE NRTS AREA*

*These items are presented here by title only. The information normally presented under these headings has been presented in connection with the HTRE Hazards Report, see APEX 180.

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